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Advanced Finite Element Modelling of Composite Beams with High Strength Materials and Deformable Shear Connectors

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Abstract

This paper presents a comprehensive numerical investigation into the structural behaviour of simply supported composite beams with high strength materials and deformable shear connectors. Advanced two and three dimensional finite element models of the simply supported composite beams are established, and they have been carefully calibrated against the results of two test beams reported in the literature. The two dimensional finite element models are then extended to investigate the structural behaviour of simply supported composite beams with different combinations of high strength steels and concrete. A number of key findings of the numerical investigation are presented after careful consideration on the predicted moment capacities of the composite beams determined from various methods. It is shown that an elasto-plastic stress distribution should be adopted to determine the moment capacities of composite beams using a wide range of steel and concrete materials with high structural adequacy.

Keywords: Composite beams; Shear connectors, High strength materials; Finite element models

1. Introduction

In general, composite beams are strong and stiff flexural members with long spanning capacities. The structural form of a composite beam is essentially a thin wide concrete slab connected intermittently through the use of shear connectors with a steel section. A certain depth of the concrete slab is in compression while the steel section is largely in tension. It maximizes the structural advantages of both the concrete slab and the steel section, and is widely used in building construction for many years owing to their high constructability. Shear connectors, usually headed studs, are welded to the top flanges of the

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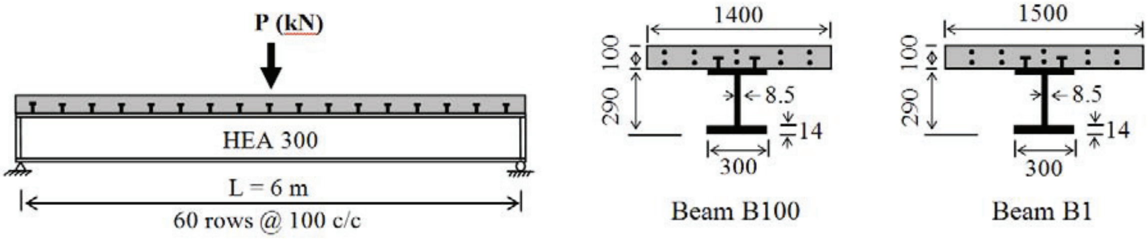
steel sections and fully embedded into the concrete slabs. In order to mobilize their shear resistances at the steel-concrete interfaces, the shear studs have to deform while the slippage limits in many headed shear studs in solid concrete slabs are found to be 5 to 7 mm.

In the recent years, there is a steady trend to use high strength materials in building construction as they provide increased load carrying capacities without increasing the dimensions as well as the dead loads or the self-weights of a structure. This paper presents a numerical investigation into the moment capacities of composite beams, and comparisons with current design methods are also reported and discussed.

2. Calibration of finite element models

In order to simulate numerically the structural behaviour of composite beams with high strength materials and deformable shear connectors, three dimensional finite element models are established using the general purpose finite element package ABAQUS (ABAQUS 2004). Two simply supported composite beams, namely Beam B100 reported by Hanswille (EUR20104 2002) and Beam B1 reported by Hegger (EUR20104 2002) are adopted in the calibration of the proposed finite element models. The geometrical details of the beams are illustrated in Figure 1 together with their loading and support conditions.



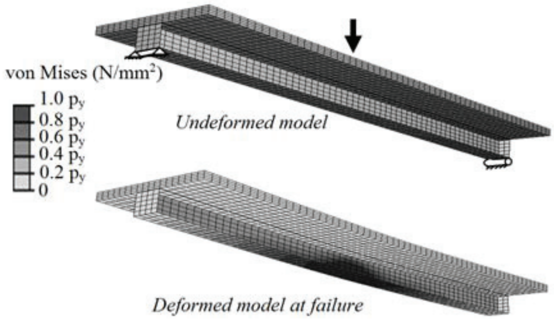
(a) Geometrical details

Beam	Steel section		Steel reinforcement	Concrete
	Flange	Web		
	Yield strength, p_y (N/mm^2)	Yield strength, p_y (N/mm^2)	Yield strength, p_{yr} (N/mm^2)	Cylinder strength, f_{ck} (N/mm^2)
B100	458	488	591	79
B1	508	508	579	31

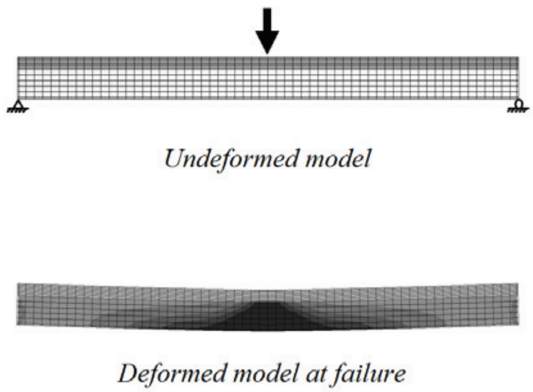
(b) Mechanical strengths

Figure 1: Details of Beams B100 and B1

It should be noted that shell elements S4 and solid elements C3D8 are employed to model the steel sections and the concrete slabs respectively of the three dimensional models of the composite beams, as shown in Figure 2(a). Moreover, since the principal failure modes in composite beams involve primarily in-plane deformation while out-of-plane instability is expected not to be critical, two dimensional finite element models as shown in Figure 2(b) are also employed in the numerical calibration for comparison. Iso-parametric plane stress elements CPS4R are employed to model both the steel sections and the concrete slabs.



(a) Three-dimensional model

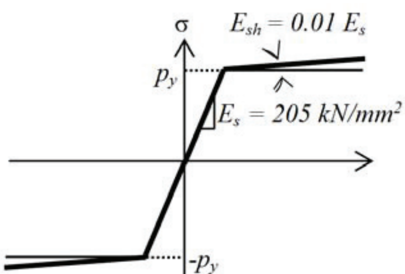


(b) Two-dimensional model

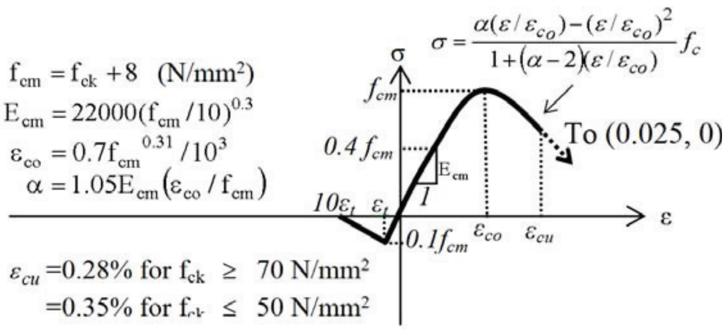
Figure 2: Finite element modelling of Beam B100

2.1 Material models of steel and concrete

Material and geometrical non-linearity is fully incorporated into the finite element models. The material models of the steel section, the reinforcement and the concrete according to Eurocodes 2 (BSI 2004) and 3 (BSI 2006) are illustrated in Figure 3 for details.



(a) Steel section and reinforcement



(b) Concrete

Figure 3: Stress-strain curves of steel and concrete materials

2.2 Shear connectors

As shown in Figure 4, the load-slippage curves of a shear connector obtained from standard push-out tests with both low and high strength concrete (Hegger, EUR20104 2002) are adopted into the models. For simplicity, all the beams are assumed to operate under full shear connection, and hence, the slippage of the shear studs ranges from 0.2 to 0.36 mm. Hence, all the shear studs perform in a ductile manner in the present study, and each shear stud is modelled with one longitudinal spring, one transverse spring and one vertical spring in order to simulate the longitudinal force, the transverse shear force as well as the pull-out force of the shear stud respectively.

2.3 Check points

In order to define failure in the composite beams, the following check points are established:

- Check point for concrete

Limiting compressive strain in the concrete, ε_{cmax}, at 0.35 % in Grade C30/37 concrete, and 0.28 % in Grade C80/95 concrete, according to Eurocode 2 (BSI 2004).

- Check point for steel

Monitoring tensile strain in the steel section, ε_{smax}, at $c_o \times \frac{p_y}{E_s} \times \sqrt{\frac{p_y}{275}}$ where c_o is the deformation coefficient taken to be 6; p_y is the yield strength of the steel section; and E_s is the Young's modulus of the steel section.

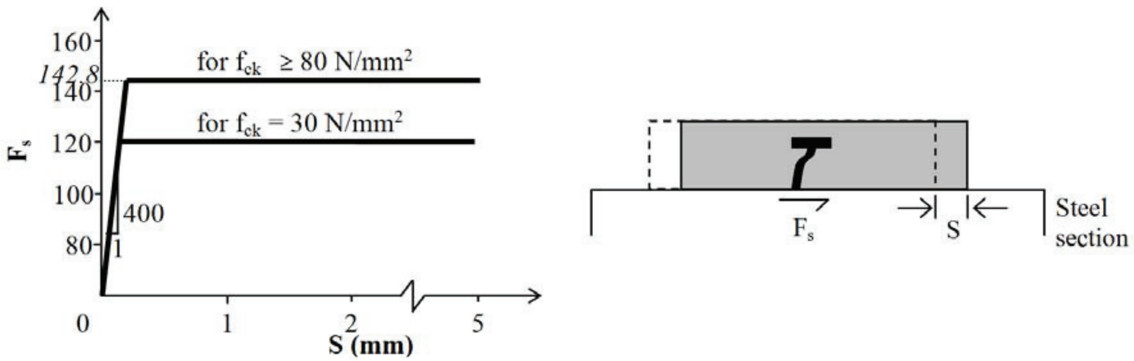


Figure 4: Load-slippage curves of a shear connector

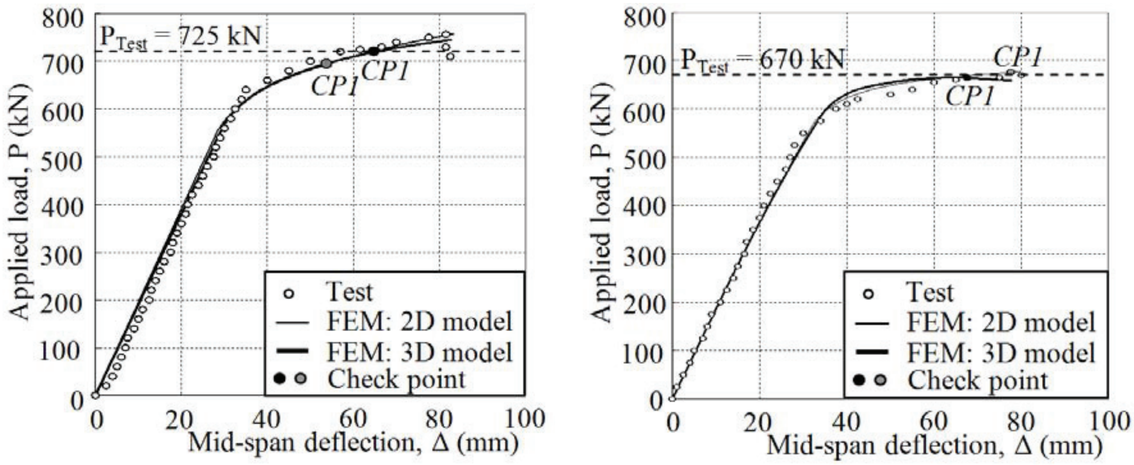
2.4 Load-deflection curves

Figure 5 presents the load-deflection curves obtained from the two and the three dimensional models of Beams B100 and B1 together with the test data for easy comparison. It is shown that both the numerical curves derived from the two and the three dimensional models follow closely to the test data not only in the elastic deformation ranges but also in the large deformation ranges. In general, owing to the abundant provision of shear connectors in both beams, the maximum slippages in the shear connectors are found to be smaller than 1.0 mm.

2.5 Load carrying capacities and model factors

As high strength steels are used in the beams, concrete crushing is found to be critical in both finite element models. Hence, the predicted failure loads of the models at the lowest check point, i.e. check point against concrete crushing, obtained from the two and the three dimensional models are summarized in Table 1 together with the measured failure loads of the composite beams. Moreover, a model factor is established to assess structural accuracy of the proposed models.

It is shown that the model factors of the two dimensional models are found to be 1.0 and 0.99 for Beams B100 and B1 respectively while those of the three dimensional models are 1.04 and 1.01 respectively. Hence, the finite element models are demonstrated to be highly effective. As the differences in the numerical results between the two and the three dimensional models are very small, it is considered to be adequately accurate to employ two dimensional models to examine the structural behaviour of simply supported composite beams with different combinations of high strength materials.



Beam B100 Beam B1

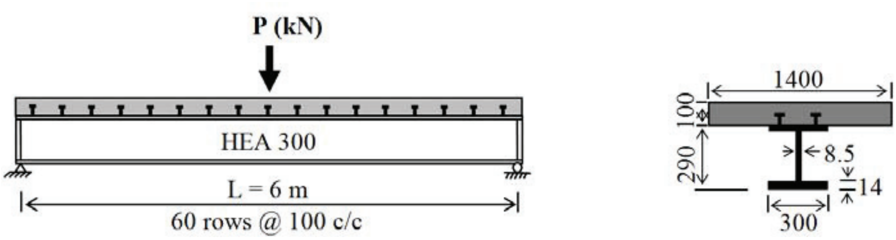
Figure 5: Load deflection curves of Beams B100 and B1

Table 1: Summary of load carrying capacities of test beams

Beam	Measured failure load	Predicted failure load		Model factor	
	P_{Test} (kN)	$P_{FEM,2D}$ (kN)	$P_{FEM,3D}$ (kN)	P_{Test} / $P_{FEM,2D}$	P_{Test} / $P_{FEM,3D}$
B100	725.0	721.5	695.2	1.00	1.04
B1	670.0	676.0	664.5	0.99	1.01

3. Parametric study

As shown in Figure 6, a parametric study on simply supported composite beams is conducted with the same geometrical dimensions of Beam B100, but with different material strengths.



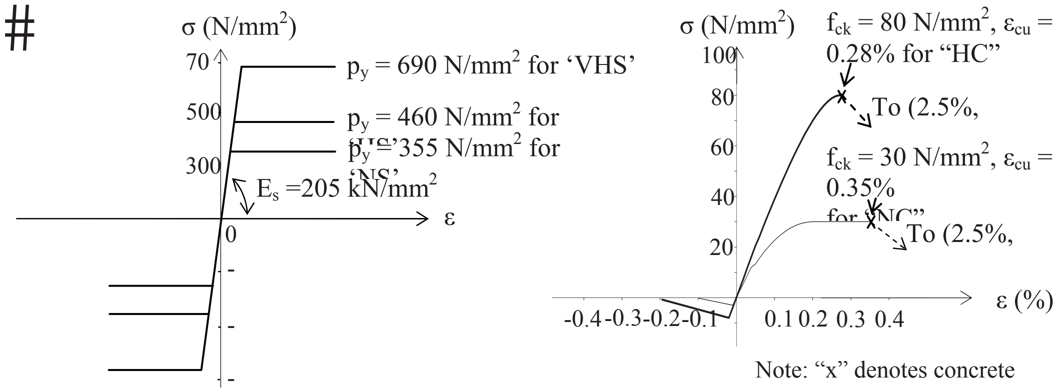
(a) Geometrical details

Beam	Steel section	Concrete	Degree of shear connection, k_{sc}
	Yield strength, p_y (N/mm^2)	Cylinder strength, f_{ck} (N/mm^2)	
HC-VHS	690	80	1.17
NC-VHS	690	30	2.02
HC-HS	460	80	1.75
NC-HS	460	30	2.02
HC-NS	355	80	2.27
NC-NS	355	30	2.02

(b) Material strengths

Figure 6: Summary of the parametric study

The material models of the steel sections and the concrete illustrated in Figure 7 are adopted in the finite element models. Moreover, the load-slippage curves of the shear studs with both normal and high strength concrete shown in Figure 4 are also adopted. Furthermore, both the check points given in Section 2.3 are also adopted to identify the failure loads of the models.



(a) Steel section (b) Concrete

Figure 7: Stress-strain curves of steel and concrete in the parametric study

3.1 Numerical results

The load-deflection curves of the six beams are plotted onto the same graph in Figure 8 for direct comparison. Check points are also plotted onto the curves to identify the failure loads of the composite beams. As shown in Figure 8, it is found that:

- In general, the load deflection curves of the beams are fairly ductile, allowing large tensile strains to be developed at the bottom flanges of steel sections at mid-span. In all cases, the beams fail in concrete crushing.

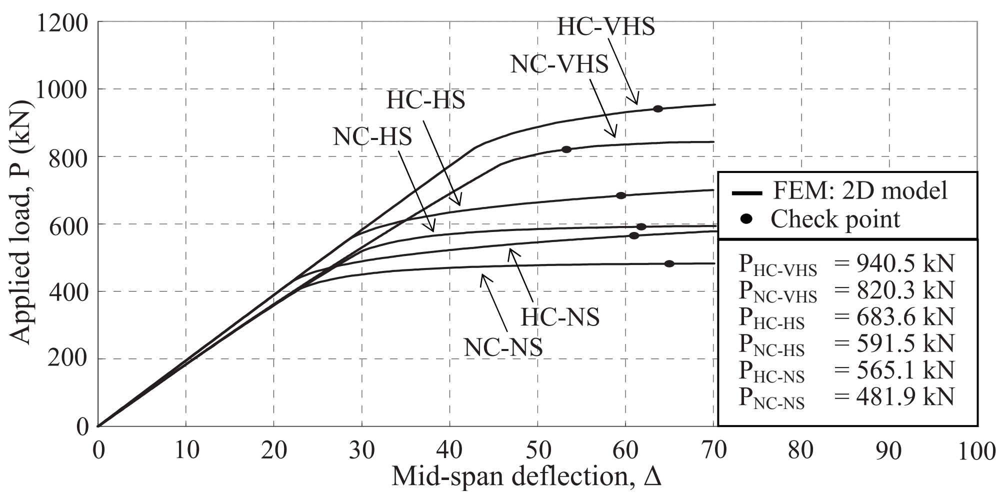


Figure 8: Load deflection curves of various beams in the parametric study

- For composite beams with normal strength concrete but with steel sections of different design strengths, namely, Beams NC-VHS, NC-HS and NC-NS, their load carrying capacities are found to be 820.3, 591.5 and 481.9 kN respectively. This corresponds to an increase of 70.2 and 22.7 % in their load carrying capacities with S690 and S460 steel sections, when compared with that of a composite beam with a S355 steel section.
- For composite beams with normal strength steel but with concrete of different compressive strengths, namely, Beams HC-NS and NC-NS, their load carrying capacities are found to be 565.1 and 481.9 kN respectively. This corresponds to an increase of 17.3 % in the load carrying capacity with C80/95 concrete, when compared with that of a composite beam with C30/37 concrete.

3.2 Stress distributions

Figure 9(a) illustrates typical stress distribution of the composite beams obtained from the finite element models. For comparison purpose, the stress distribution according to the plastic stress block analysis adopted in Eurocode 4 is also shown in Figure 9(b). Owing to the use of high strength steel, Eurocode 4 (BSI 2002) recommends a reduction to the moment capacities of the composite beams according to the value of h_o/h, where h_o is the depth of the concrete in compression, and h is the overall depth of the composite beam. The moment capacities obtained from Eurocode 4 are denoted as M_{EC4}.

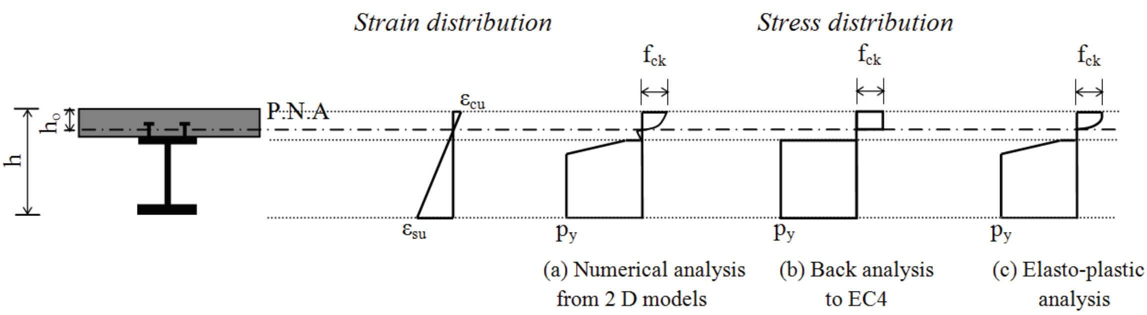


Figure 9: Stress distributions of the composite beams in the parametric study

However, it is considered necessary to adopt a new stress distribution in which the top flange of the steel section is not working at its full yield strength, as shown in Figure 9(c). This often happens in composite beams with high strength steels, in particular, when the plastic neutral axes are close to the top flanges of the steel sections. The moment capacities determined according to the proposed elasto-plastic stress distribution is denoted as M_{EP}.

3.3 Comparison on moment capacities from various methods

The moment capacities of the composite beams obtained from the finite element models, the codified method and the proposed method are summarized in Table 2 for easy comparison. It is found that:

- For Beam HC-NS (with $h_o/h = 0.10$) and Beam NC-NS (with $h_o/h = 0.26$), no reduction is needed according to Eurocode 4. The corresponding model factors M_{FEM}/M_{EC4} and M_{FEM}/M_{EP} are found to be 1.00, and this demonstrates that Eurocode 4 is able to provide good estimation to the moment capacities of composite beams with normal strength steel of S355.
- For Beam HC-HS (with $h_o/h = 0.13$) and Beam NC-HS (with $h_o/h = 0.27$), reduction to the moment capacities is needed according to Eurocode 4. The corresponding model factors M_{FEM}/M_{EC4} are found to be 0.96 and 1.08 respectively.

For Beam HC-VHS (with h_o/h = 0.20) and Beam NC-VHS (with h_o/h = 0.30), reduction to the moment capacities is also needed according to Eurocode 4, and the corresponding model factors M_{FEM}/M_{EC4} are found to be 0.96 and 1.10 respectively.

- This shows that Eurocode 4 tends to overestimate the moment capacities of the composite beams with high strength concrete (C80/95) by 4%, but underestimates the moment capacities of the composite beams with normal strength concrete (C30/37) by about 8 to 10 %.
- However, the model factors M_{FEM}/M_{EP} for all the composite beams are found to be very close to 1.00, and this demonstrates that the proposed method is able to provide good estimations to the moment capacities of composite beams with a wide range of steel and concrete strengths.

Table 2: Summary of the moment capacities of composite beams

Beam	Numerical analysis		Back analysis		Elasto-plastic analysis		Model factor		
	M_{FEM} (kNm)	h_o / h	M_{PSB} (kNm)	M_{EC4} (kNm)	h_o / h	M_{EP} (kNm)	M_{FEM} / M_{PSB}	M_{FEM} / M_{EC4}	M_{FEM}/ M_{EP}
HC-VHS	1410.8	0.20	1514.1	1471.7	0.20	1421.2	0.93	0.96	0.99
NC-VHS	1230.5	0.30	1224.6	1114.4	0.30	1254.9	1.00	1.10	0.98
HC-HS	1025.4	0.13	1072.7	1072.7	0.17	1042.1	0.96	0.96	0.98
NC-HS	887.3	0.27	884.2	821.2	0.25	892.0	1.00	1.08	0.99
HC-NS	847.7	0.10	849.5	849.5	0.14	849.1	1.00	1.00	1.00
NC-NS	723.0	0.26	725.4	725.4	0.22	730.1	1.00	1.00	0.99

Notes: 1) MPSB is the moment capacity determined with the plastic stress block analysis.
2) MEC4 is the moment capacity according to EC4 with reduction as appropriate.
3) MEP is the moment capacity determined with the elasto-plastic analysis proposed by the authors.

4. Conclusion

This paper presents a comprehensive numerical investigation into the structural behaviour of simply supported composite beams with high strength materials and deformable shear connectors. It is found that for composite beams under full shear connection, the moment capacities will be readily increased by 20 to 70 % if the yield strengths of the steel sections are increased from 355 N/mm^2 to 460 and 690 N/mm^2 respectively, without increasing their self-weights. Moreover, for composite beams with high strength steels (S460 or S690), Eurocode 4 overestimates the moment capacities of composite beams by 4 % when high strength concrete (C80/95) is used whilst it underestimates the moment capacities by 8 to 10 % when normal strength concrete (C30/37) is used. It is also demonstrated that the use of elasto-plastic stress distribution allows accurate prediction on the moment capacities of composite beams using a wide range of steel and concrete materials.

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